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Range shifts of a relict Himalayan dragonfly in the Hindu Kush Himalayan region under climate change scenarios

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Although understanding of geographic range shifts of many species in response to global climate change is expanding steadily, little is known about the Himalayan fauna, which in particular is affected by relatively faster warming rates than other parts of the world. Anticipated increases in temperature and changes in hydrological regimes will have significant adverse impacts on the habitat suitability for many species. This threat will even be higher to endemic and already threatened species due to their restricted distribution and narrow climate tolerance ranges. We investigated the range shifts of a relict Himalayan dragonfly (*Epiophlebia laidlawi*), a species that is endemic to the Hindu Kush Himalayan region. Currently, the species is only known from few localities in Bhutan, India and Nepal. For conservation of the species, it is necessary to foresee potential suitable habitat areas and range shifts due to global climate change. Here, we first estimated the current potential geographic distribution by identifying the suitable habitat area in the region using bioclimatic envelope models, by means of consensus projections of six algorithms as implemented in the BIOMOD-package in the software program R. We then used the current distribution to render future projections under the A2a and B2a IPCC emission scenarios for the years 2050 and 2080. Models predict that the suitable habitat area of the species will shift on average 374 m and 599 m uphill under the extreme (A2a) climate warming scenario, and 294 m and 342 m uphill under the moderate (B2a) scenario by 2050 and 2080, respectively. Future suitable habitat areas are projected to remain only in the high mountains of eastern Nepal. The results will help conservationists to delineate priority habitats in the first step towards the species conservation in the region.

Keywords: Odonata; dragonfly; climate change; *Epiophlebia laidlawi*; bioclimatic envelope model; suitable habitat area; altitudinal range shifts; conservation

Introduction

The degree of anthropogenic climate warming over the past 50 years appears to increase with elevation in the Hindu Kush Himalayan (HKH) region, as observed in Tibet and Nepal, with warming more pronounced in winter than in summer (Cruz et al., 2007; Liu & Chen, 2000; Shrestha et al., 1999; Yang et al., 2011). The United Nation's climate change technical advisory group, the Intergovernmental Panel on Climate Change (IPCC), has projected that the average

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annual mean air warming will be about 3°C and 5°C in the decades of the 2050s and 2080s, respectively, over the Asian landmass (Cruz et al., 2007). Air temperature, precipitation and run-off patterns have been implicated in altering the structure of aquatic communities (Burgmer et al., 2007; Heino, 2002; Heino et al., 2009) and change in the distribution of suitable habitat (Hassall & Thompson, 2008).

In the case of the HKH region, various studies have focused on climate change and its consequent effects on glacier retreats, vegetation shifts, life zone shifts and livelihoods (Bajracharya et al., 2008; Ni, 2000; Song et al., 2004; Xu et al., 2009; Yao et al., 2007; Zhang et al., 1996). In contrast, very few publications have described the cascading effects of environmental change on aquatic biodiversity. There is a clear lack of information on changes of suitable habitats and range shifts of freshwater species under changing climate scenarios (e.g. Pandit, 2009). Rare and endemic species require special attention in particular because they are likely to be highly sensitive to impacts on their habitats from climate change and may have difficulties shifting their range to new areas. Slight environmental changes can lead to habitat shifts or cause the species to perish at local or regional levels.

Epiophlebia laidlawi, an endemic species, is one of the three species that exist in the living Anisozygoptera (Epiophlebiidae-family) suborder. The species was originally described by Tillyard (1921) from Darjeeling Himalaya and recorded for the first time in Nepal at the Tamar River (Asahina, 1963), in and around Thimphu area of Bhutan by Brockhaus and Hartmann (2009). It was categorized by the International Union for Conservation of Nature (IUCN) as a near threatened invertebrate in 2010 (IUCN, 2010). In India, the species was considered as a threatened taxon by Mitra (2002). This regional endemic species inhabits mostly headwater mountain streams with minimal anthropogenic impact. The species may be vulnerable to environmental change because of its biological and ecological traits; for instance, its partivoltine reproductive nature (Corbet et al., 2006), small population size, narrow habitat tolerance, and its survival only within restricted geographic ranges in the Eastern Himalaya biodiversity hotspot of the HKH region.

For effective long-term conservation and protection of the endemic species, there is an urgent need to anticipate potential habitat area at present and in future. This will help in accurate detection and precise monitoring of the species in the region. This study is intended (1) to identify the current potential suitable habitats; and (2) to simulate future range shifts of the potential suitable habitat of the species in the HKH region under different climate scenarios until 2050 and 2080 by using bioclimatic envelope models (BEMs). Future projections are made under the extreme assumptions of no dispersal and full dispersal (i.e. the species is able to colonize all locations that are predicted to become suitable). Modelling of the potential distribution of species provides the possibility of identifying critical and suitable habitat under different climate scenarios. This may not only alert conservationists but also help to allocate resources and adopt conservation measures in time for those critically affected geographic areas.

Materials and methods

Study area

The study region covers the Hindu Kush Himalaya, situated in South Asia (60°85′–105°04′E, 15°96′–39°32′N; Figure 1). The area has a spatial extent of about 3500 km from Afghanistan in the west to Myanmar and China in the east, and includes Pakistan, India, Nepal, the Tibetan Plateau, Bangladesh and Bhutan. The altitude ranges from below 100 m asl to 8848 m asl at Mount Everest. Consequently, it encompasses a steep climatic gradient from tropical to extreme alpine climates. The regional climate is strongly influenced by the south-Asian monsoon.

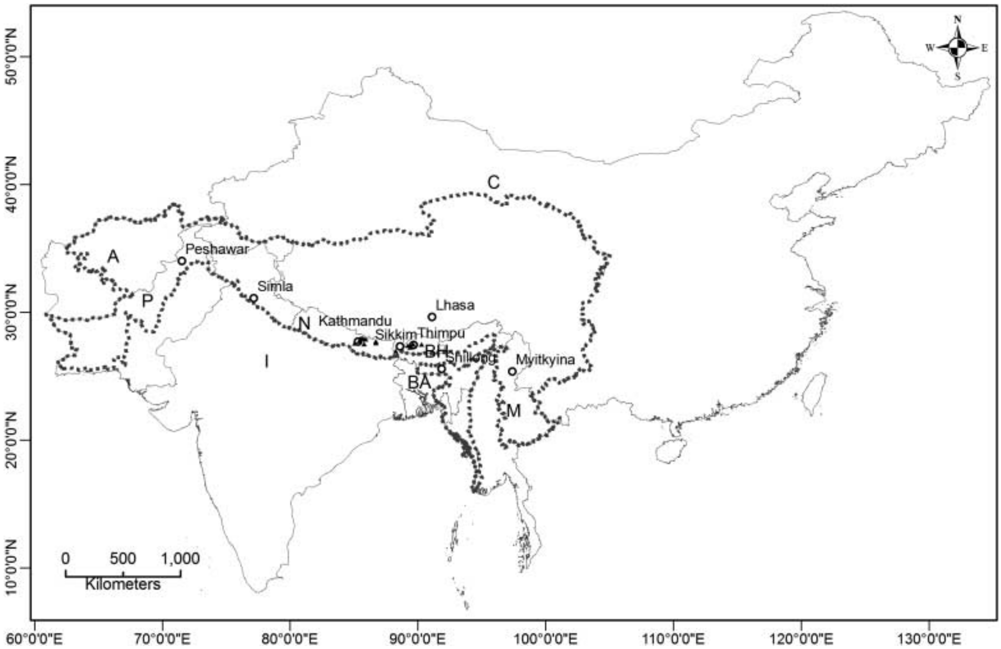

Figure 1. The partner countries of the Hindu Kush Himalayan (HKH) region in South Asia. Abbreviations (left to right): A, Afghanistan; P, Pakistan; I, India; N, Nepal; C, China; BH, Bhutan; BA, Bangladesh; M, Myanmar. Countries are delineated with smooth lines, while the HKH region is shown with a dotted boundary line (- - -). The open circles (○) and filled triangles (▲) represent major cities of the respective countries and presence records of *E. laidlawi*, respectively.

Species data

Epiophlebia laidlawi distribution records for Nepal were based on samplings carried out by the first two authors between 2007 and 2009, as well as on literature surveys (Nesemann et al., 2011; Sharma & Ofenböck, 1996). Records from India and Bhutan were drawn from Asahina (1958) and Brockhaus and Hartmann (2009), respectively. Presence records were resampled at a spatial resolution of 2.5 arc-minutes to match the resolution of environmental predictors. In total, 22 presence records were used for the modelling approach.

Environmental predictors

We selected the environmental predictors for describing the distribution of *E. laidlawi* from a set of over 20 predictors by expert knowledge and by avoiding colinearity among predictors (Pearson correlation coefficients, $-0.7 \leq r \leq 0.7$, Green, 1979).

Four climatic predictors consisting of the annual mean temperature, mean diurnal range, isothermality (mean diurnal temperature range divided by the annual temperature range) and annual precipitation were selected. Present and future climatic predictors with a spatial resolution of 2.5 arc-minutes (approximately 5 km^2) were downloaded from the WorldClim database (http://www.worldclim.org, accessed 8 August 2011, Hijmans et al., 2005). To overcome uncertainties derived from future climatic projections, we used bioclimatic predictors of the years 2050 and 2080 derived from four global climate models (CCCMA-CGCM2, Flato et al., 2000; HCCPR HADCM3, Gordon et al., 2000; CSIRO-MK2, Gordon et al., 2002; and NIES99, Emori et al., 1999). For each, we used the A2a ("extreme") and B2a ("moderate") climate warming scenario of the 4th Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2007).

Bioclimatic envelope models

We fitted presence-only BEMs for *E. laidlawi* with the BIOMOD package version 1.1.7 in R (R Development Core Team, 2011; Thuiller et al., 2009). Six algorithms consisting of three regression methods (generalized linear models, GLM; generalized additive models, GAM; multiadaptive regression splines, MARS) and three machine learning methods (gradient boosting machine, GBM; artificial neural networks, ANN; random forest, RF) were used. To model the present distribution of *E. laidlawi*, we split the species presence records into a training set (70%) and a testing set (30%) by applying a random partition (Araújo et al., 2005), while 10,000 randomly drawn pseudo-absences were used. Prevalence was set at 0.5 (weighted prevalence) and each algorithm was set to a 10-fold cross validation which yielded an average model. We then projected these averaged models, which were calibrated under the present conditions, into the year 2050 and 2080 using future bioclimatic predictors from the four global climate models.

Model evaluation was conducted by means of area under curve (AUC) statistics from a receiver operating characteristic analysis, which is a threshold-independent evaluation of model discrimination (Fielding & Bell, 1997). AUC values range from 0.5 to 1, where 0.5 describes a discrimination no better than random, while 1 describes perfect discrimination (Hosmer & Lemeshow, 2000). Since a consensus projection significantly improves the predictive accuracy of BEMs (Araújo et al., 2005), we used weighted averages based on the predictive performance of single model outputs for each algorithm. The relative importance of each algorithm for the final consensus models was obtained by multiplying the averaged AUC value with a weight decay of 1.6 (default settings). To reduce uncertainties derived from the four global climate models, we averaged the species predictions to receive a single A2a and B2a projection for the years 2050 and 2080. Occurrence probability maps of present and future projections were finally transformed into binary presence-absence maps by applying a cut-off value which minimizes the difference between sensitivity (true positive predictions) and specificity (true negative predictions, Fielding & Bell, 1997).

Response of E. laidlawi *to climate change*

Altitudinal shifts of *E. laidlawi* were analysed using the mean altitude of the species' suitable habitat area in the present distribution, and the mean altitude of future suitable habitat area under the A2a and B2a scenarios of 2050 and 2080, respectively.

Species range changes were calculated under the assumptions of (1) no dispersal, and (2) unlimited dispersal for *E. laidlawi*. Here, the difference between the number of grid cells gained and lost as a percentage of the number of grid cells presently classified as suitable habitat was used.

The relative contribution of each environmental predictor for describing the distribution of *E. laidlawi* was obtained by averaging the results from each algorithm using the identical weights for creating the final consensus projections.

Results

Model performance

Model performance for *E. laidlawi* was good with a consensus AUC of 0.99, and percentages of sensitivity (true positive predictions) and specificity (true negative predictions) were 90.91 and 94.85, respectively. The annual mean temperature contributed most strongly (33%) to the species' present distribution, while the annual mean precipitation, the isothermality, and the mean diurnal range contributed 25, 23, and 19% to the present distribution, respectively.

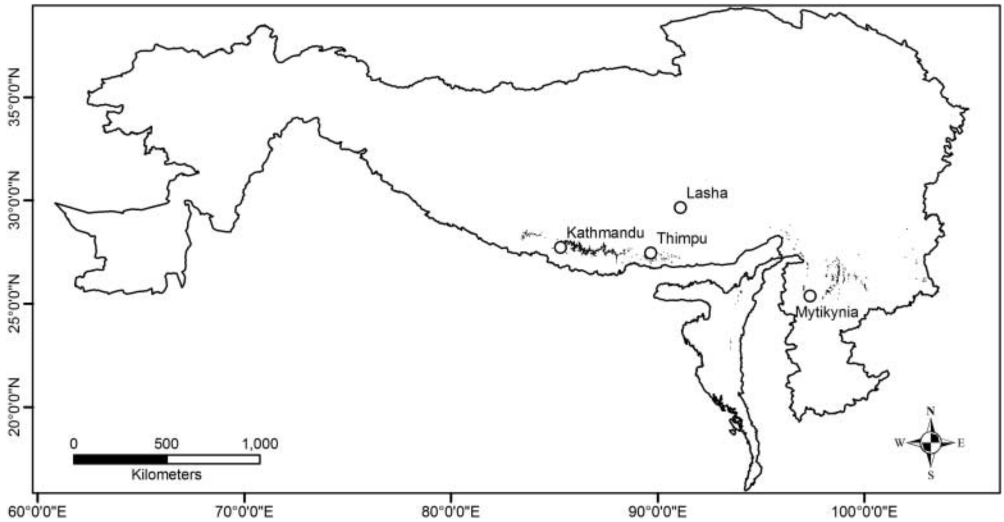

Figure 2. Boundary of the Hindu Kush Himalayan (HKH) region with the current simulated suitable habitat areas of *E. laidlawi* (shaded areas). The circles (o) represent major city locations.

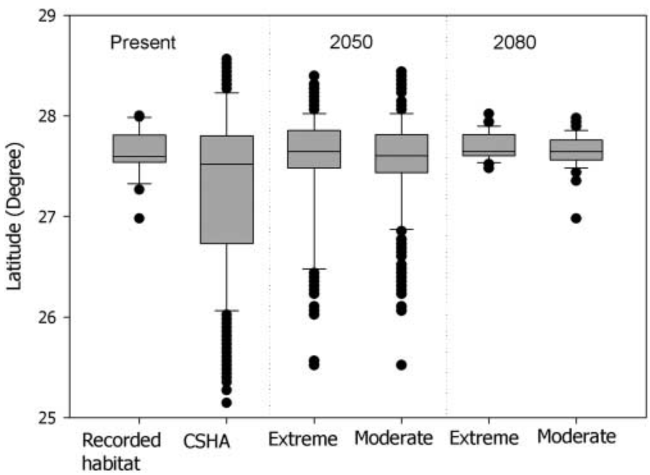

Figure 3. Latitude box plot of *E. laidlawi*'s presence records, the current simulated suitable habitat areas (CSHA), and predicted suitable habitat areas under the "extreme" (A2a) and "moderate" (B2a) emission scenarios for 2050 and 2080 years. The lower, middle and upper lines of each box represent 25th percentile, median, and 75th percentile, respectively. Dark circles represent outliers.

Current distribution of **E. laidlawi**

The recorded localities of *E. laidlawi* range from 26.97°N to 28.00°N latitudes, and altitudes between 1300 and 2885 m asl, while predicted current potential habitat distribution (Figure 2) ranged from 25.14°N to 28.56°N latitudes (Figure 3), and altitudes between 932 and 3738 m asl (Figure 4). The current projected suitable habitat area extends continuously from western to eastern Nepal, at Darjeeling and west to east of Bhutan. Moreover, the model predicts suitable habitat areas in the south-western part of China (Yunnan) and north-eastern part of Myanmar (Figure 2).

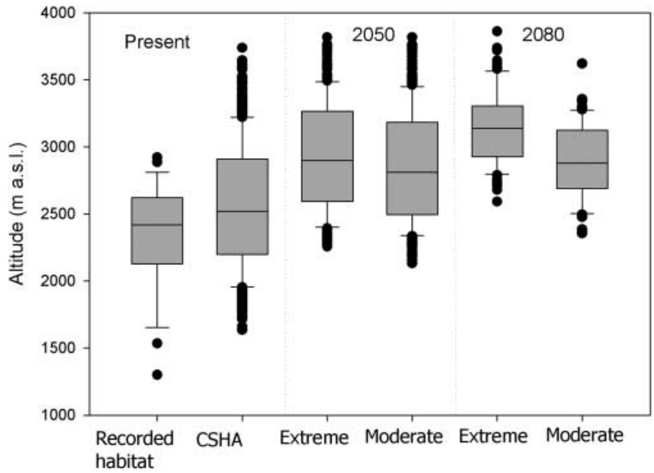

Figure 4. Altitude box plots of *E. laidlawi*'s presence records, the current simulated suitable habitat area (CSHA), and predicted suitable habitat area under the "extreme" (A2a) and "moderate" (B2a) emission scenarios for 2050 and 2080 years. The lower, middle and upper lines of each box represent 25th percentile, median, and 75th percentile, respectively. Circles represent outliers.

Table 1. Expected changes in the altitudes and latitudes derived from bioclimatic envelope models of *E. laidlawi* to 2050 and 2080 in the Hindu Kush Himalayan region under the A2a ("extreme") and B2a ("moderate") emission scenarios.

	Altitude (m)		Latitude (°)	
IPCC emission scenario/years	Mean	SD	Mean	SD
Present	2559	461	27.26313	0.806200
A2a_2050	2933	395	27.53321	0.548553
A2a_2080	3158	279	27.69618	0.138447
B2a_2050	2854	409	27.54339	0.478877
B2a_2080	2901	283	27.65351	0.142056

Future potential distributions of E. laidlawi *in the face of climate change*

The future distribution of *E. laidlawi* was predicted to contract over time for both no and full dispersal assumptions. Under the A2a scenario, the average latitude of the species' suitable habitat area would shift slightly higher from the current mean latitude 27.26° N to 27.53° N by 2050 and to 27.70° N by 2080 (Table 1, Figure 3). In contrast, the species' suitable habitat area would shift considerably towards higher elevations, by 374 m by 2050 and by 599 m by 2080 from the present mean altitude of 2559 m asl (Figure 4). The reduction of suitable habitats corresponds to a 71% loss of habitat compared to a compensatory gain of only 8% by 2050, and a habitat loss of 90% compared to a gain of 3% by 2080 (Figure 5a, b). In this scenario, the future suitable habitat area would remain in central and eastern Nepal and would disappear completely from other eastern parts of the region.

Under the B2a scenario, the extension of latitude was similar to the A2a scenario. The average altitude of the species' suitable habitat area would shift to higher elevations of 295 m and 342 m by 2050 and 2080, respectively from the present mean altitude (2559 m asl). The habitat loss would be 69% and 83% by 2050 and 2080, respectively (Figure 5c, d), while the gain of suitable habitats would be 11% and 3% by 2050 and 2080. This range shift and the strong reduction in habitat size showed an extensive loss of the present habitat (Figure 6).

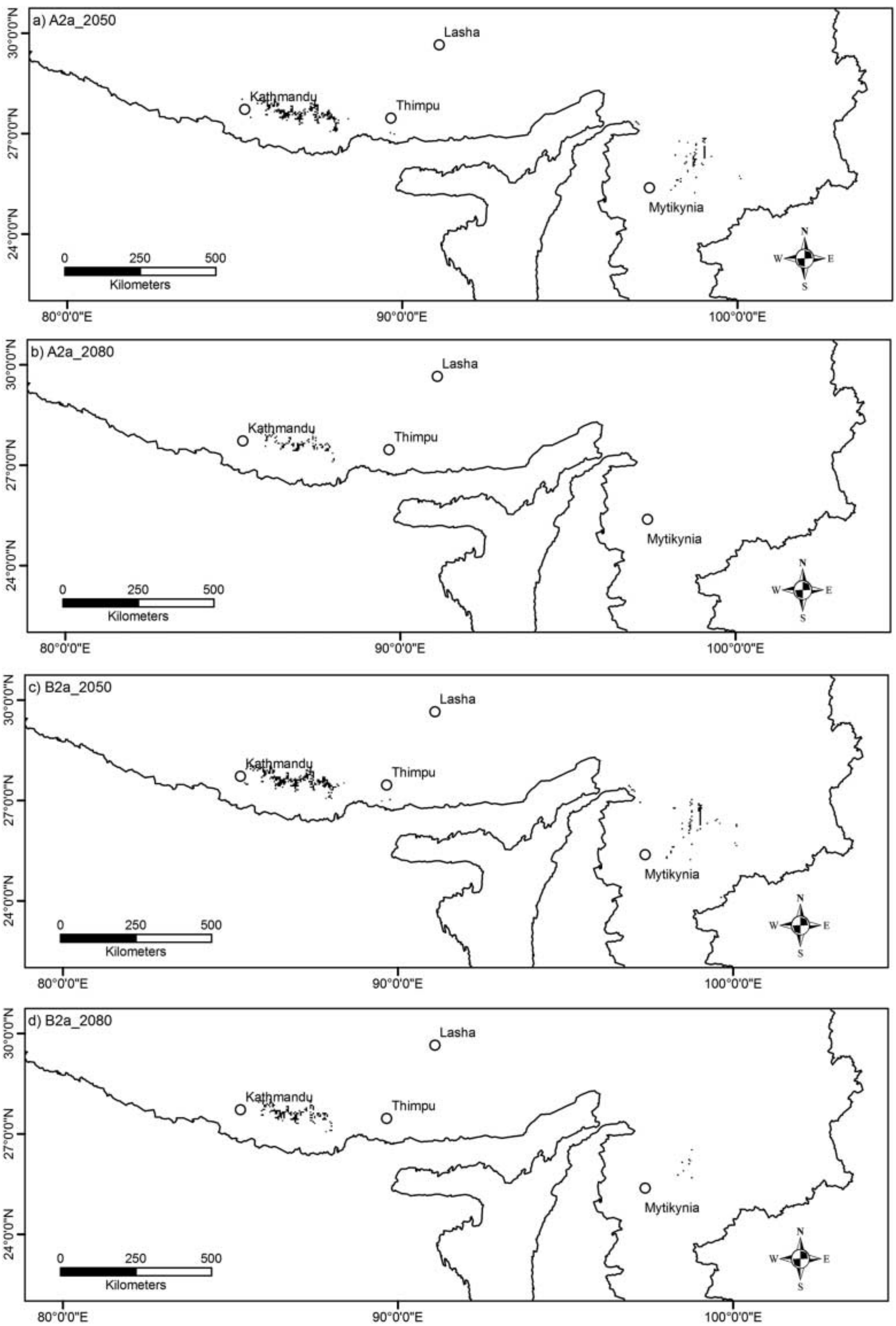

Figure 5. Predicted suitable habitat areas of *E. laidlawi* in the years (a, c) 2050 and (b, d) 2080 under the (a, b) A2a ("extreme") and (c, d) B2a ("moderate") emission scenarios (shaded areas). The circles (o) represent major city locations.

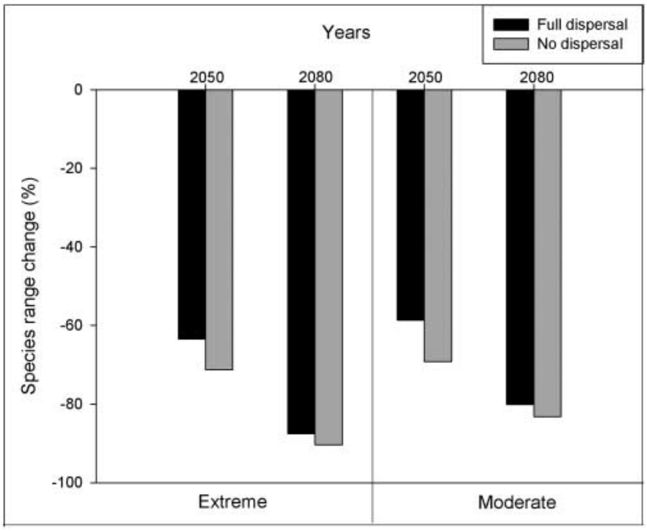

Figure 6. Predicted range size changes of *E. laidlawi*'s suitable habitat considering full dispersal and no dispersal assumptions by 2050 and 2080 under the "extreme" (A2a) and "moderate" (B2a) emission scenarios.

Discussion

Current distribution of E. laidlawi

The simulated current projection of *E. laidlawi* is consistent with its actual distributions, which has predicated narrow geographic ranges in both latitude and altitude as assumed for the species. This implies that at this spatial scale and resolution, the environmental predictors (annual mean temperature, isothermality, annual mean precipitation and mean diurnal range) used in the BEMs are crucial factors in determining the range limits of this relict species (*sensu* Pearson & Dawson, 2003). Since these predictors in the mountain headwater streams are strongly affected by weather patterns (in the short term) or climate (long term), *E. laidlawi* inhabiting these systems is especially sensitive to climate change. Its partivoltine reproductive nature, narrow thermo-neutral zone, and obligatory relationship to a natural patchy habitat will seriously threaten the species' existence in the face of climate change. The species' survival will also be highly dependent on the magnitude of contemporary anthropogenic activities such as degradation of forests, habitat alteration, pollution and changing land use patterns.

Previous research (Asahina, 1958; Brockhaus & Hartmann, 2009; Nesemann et al., 2011; Sharma & Ofenböck, 1996; Tani & Miyatake, 1979) recorded the species from headwater streams in Darjeeling, India; the Shivapuri Hills and Simbhanjyang of central Nepal; Eastern Nepal and west to the central region of Bhutan (Haa to Trongsa district). Our simulated model also corroborated these areas as suitable habitat areas of the species. It has further confirmed that the headwater (tributaries) of the Bhote Koshi River in Nepal section until a few kilometres upstream in Tibet is also a suitable habitat for the species. This area was also hypothesized as possibly harbouring *Epiophlebia* species by Sharma and Ofenböck (1996). Besides these areas, our model predicted a larger current suitable habitat range (north-eastern part of Myanmar and south-western part of China) of the species in the region. The predicted areas may be appropriate in ecological terms, but the species might not occur in all potential areas due to a variety of historical and ecological reasons (Peterson et al., 1999). Nevertheless, the recent records of the species from Bhutan (Brockhaus & Hartmann, 2009) and new localities in Nepal (Nesemann et al., 2011) suggest that more areas inhabited by *E. laidlawi* remain to be discovered. In this regard, areas of suitable

conditions (Figure 2) would be excellent candidates for inspection, identifying source and sink populations and selection of populations for urgent conservation measures (e.g. Farnsworth & Ogurcak, 2006). Conserving the species at their local habitats will allow study of their ecological and physiological characteristics, to advance our knowledge of the Himalayan fauna in relation to climate change.

The simulated habitat distribution of rare and endemic species (e.g. *E. laidlawi*) allows for the detection of the true geographic range more readily than in ecologically tolerant eurytopic species (e.g. Finch et al., 2006). Similarly, since the potential habitats have been modelled only for the nymph, i.e. the aquatic stage of *E. laidlawi*, this reduces possible false predictions caused by the chance of migration that is generally common for most adult Odonata, causing accidental records (e.g. Schmidt, 1985). Being a lotic species, it might have a lower mobility compared to lentic Odonates (e.g., Hof et al., 2008). For instance, the distributions of butterflies in Finland with low mobility were modelled more accurately than species with high mobility (Pöyry et al., 2008). The BEMs that we applied are thus useful and valid for rendering future suitable habitat projection of the species in different IPCC emission scenarios. Though BEMs tend to strongly simplify the environment by restricting the suitable habitats of species by climatic conditions and omitting species traits and biotic interactions, they nevertheless give a first approximation of possible climate-change impacts resulting from warming temperatures and altered precipitation patterns (Pearson & Dawson, 2003).

Future distributions of **E. laidlawi**

Mountain species have been predicted to be particularly at risk from effects of contemporary climate change (Bálint et al., 2011; Hijmans & Graham, 2006; Parmesan, 2006). The distributions of mountain-dwelling species have shifted uphill during warming periods, whereas the distributions of flatland species have moved to higher latitudes (Parmesan and Yohe, 2003; Guralnick, 2007). This is why the latitudinal shifts of species are an evident phenomenon in temperate regions across Europe and North America (e.g. Hassell et al., 2010; Hickling et al., 2006). In contrast, the simulated models for *E. laidlawi* under no dispersal and full dispersal assumptions predicted that the species' suitable habitat areas would shift mostly to higher elevations rather than higher latitudes by 2050 and 2080 in the HKH region.

Elevational shifts in distribution consistent with climate change have been detected in a wide range of taxa, such as butterflies in the Sierra Nevada of California (Parmesan, 2006), relict tree species in the Tibetan Plateau (Song et al., 2004), pygmy rabbits in valleys of the Great Basin (Larrucea & Brussard, 2008), and invertebrates in a submontane region of Germany (Domisch et al., 2011). For example, butterflies had uphill range shifts of 8–20 m per decade during the late twentieth century (e.g. Hickling et al., 2006; Hill et al., 2002) and a maximum 200 km range shift has already been observed over the last 40 years (Parmesan and Yohe, 2003). Aquatic invertebrates are expected to move 83–122 m upstream by 2080 (Domisch et al., 2011).

In addition to an upward movement in average elevations, range shifts have also been observed as expansions of principally upper limits of elevation (Battisti et al., 2006; Hill et al., 2002). In contrast, the lower limit of *E. laidlawi* is expected to shift uphill most markedly, with the potential suitable habitat area of the species restricted to 2000–4000 m asl under both climate scenarios by 2050, and to 2500–4000 m asl by 2080. This could be attributed to the anticipated increase in warming climates below 2000 m asl and the permanent snow cover for almost the whole year above 4000 m asl, where the temperature is not affected even under changing climate (Armstrong, 2010). The phenomenon might have prohibited any expansion of suitable habitats for the species above 4000 m asl despite its ability to fly, which should mitigate dispersal constraints, at least to some extent (e.g. Masters et al., 2007). Thus, even in changing environments under the two scenarios, the species would not move to higher elevations than 4000 m asl.

The predicted suitable habitats will contract over time for both climate change scenarios. Even assuming that the species can disperse into all available suitable habitats, it is predicted to lose about 90% and 83% of its range by the year 2080 under the severe (A2a) and the moderate (B2a) climate scenarios, respectively. Similar results are also documented for the range restricted endangered quakka (a macropod) and montane freshwater species. About 53% of the quakka's current habitat is predicted to become unsuitable under medium-severity climate scenarios, with loss of all current suitable ranges under most severe climate scenarios (Gibson et al., 2010). Similarly, about 80% and 70% of cold-adapted montane freshwater species' current potential distributions are predicted to be lost by the end of this century under the A2a and B2a emission scenarios, respectively (Sauer et al., 2011).

Our analyses suggest that *E. laidlawi* has, and will have, a very narrow geographical distribution range with a latitudinal span of $<2°$ in the Eastern Himalayan biodiversity hotspot of the HKH region. The geographical distribution range might further be threatened by climate change induced shifting of life zones in the Himalayas (Song et al., 2004). For instance, water abstraction from the brook and water contamination from cattle grazing caused the disappearance of *E. laidlawi* from the Darjeeling hills (Svihla, 1984). The preservation of appropriate, intact habitat is a key to conservation efforts for maintaining viable populations and averting permanent habitat loss. The best protection would be the conservation of specific habitats within protected areas and nature reserves or creating such areas and reserves (Brockhaus & Hartmann, 2009; Moore, 1997). To date only two habitats from Nepal are protected, i.e. the Shivapuri hills within the Shivapuri–Nagarjun National Park and parts of the Dudhkoshi fluvial system within the Sagarmatha National Park. This is done under the National Park and Wildlife Conservation Act 2029, where deforestation and transformation of land use are prohibited, but habitat areas of Darjeeling, India and Bhutan are not yet protected.

Population dynamics in climate change

Climate change will likely bring an increasing frequency of rainy spells, resulting in a higher number of flood days and consecutive days of flood events in some parts of HKH partner countries, while some parts will have severe drought periods (Muhammed et al., 2004). The changing hydrological regimes and expected droughts will also have profound effects on meta-populations of the species and community structure at the local level. Extreme floods are likely to wash out meta-populations of the species, and it may take longer to recolonize the habitat or even result in permanent extirpation. Regarding droughts, some odonates possess drought tolerant eggs (e.g. *Lestes* spp., De Block et al., 2008) or drought resistant larvae (e.g. *Coenagrion hastulatum*, Valtonen, 1986) or rapid larval development (e.g. *Lestes sponsa*, Pickup & Thompson, 1990) to avoid drought periods, but little is known about the life-history traits of *Epiophlebia* spp. Nevertheless, populations of *Epiophlebia* spp. seem likely to be severely affected by anticipated droughts as they have one of the longest aquatic larval stages (5 to 6 years in very quickly developing larvae and 9 years in the slowly growing individuals) amongst Odonata (Tabaru, 1984).

Climate warming will also adversely affect phenology, embryonic development and rapid growth rates of the species, as is already evident from other Odonates (Hassall & Thompson, 2008; Krishnaraj & Pritchard, 1995). An empirical study conducted in *Epiophlebia superstes* (a sister species of *E. laidlawi*) concluded that increase in water temperature reduced embryonic development time by 50% (Shimura, 2005). A similar phenomenon could be hypothesized for *E. laidlawi*. The earlier hatching may in turn reduce the species' fitness to the environment, further threatening population size. The species' population size might also depend on the magnitude of lowlands species invasion (e.g. Heino et al., 2009).

It is expected that climate change effects will pose a long-term risk of range shifts and habitat loss of *E. laidlawi*. The future survival under climate change will largely depend on the species'

ability to move upstream, its capacity to disperse long distances across mountain ranges, the quality of food that it receives from the surroundings of the newly colonized area, inter-specific competition within novel community assemblages in the new area, and the degree of anthropogenic disturbances to the ecosystem (*sensu* Hassall & Thompson, 2008; Sauer et al., 2011; Sweeney et al., 1992). Additionally, physiological and life-cycle characteristics of the species will further determine the sustainable viable population sizes. To date, the species' physiological, life-cycle and adult behaviours are hardly documented. Therefore, intensive studies on the species' ecological and biological traits are imperative for enhancing our understanding of direct effects of climate change on the species.

This study does not include any estimate of direct stresses that may be placed on the aquatic ecosystems. In future studies, the potential habitat distributions could be further refined by including land transformation, biological traits such as dispersal ability, life cycle traits, local environmental parameters and expected human population density of the catchments, which directly affect the natural flow and morphological settings of the rivers.

Conclusion

The study provides a first approximation of the expected impacts of climate change on the potential habitat of the relict dragonfly (*E. laidlawi*), under the present and future anticipated climate scenarios. The changes in the potential habitat of *E. laidlawi* induced by climate change follow the expected pattern depicted by the general assumption, with shifting of suitable habitats to higher elevations and higher latitudes. The BEMs indicate that altitudinal upward shifts would likely prevail in the HKH region. Nevertheless, only small effects would occur in the latitudinal movement. Detailed knowledge on the ecology and biology of *E. laidlawi* is scarce. Thus, intensive studies focusing on the biological and ecological traits of this species should be seen as a priority to establish its vulnerability or extinction under climate change. Conservation of a variety of elevations and known aspects of mountain ranges overall will contribute to the conservation of this regional endemic Himalayan dragonfly.

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References

Araújo, M.B., Whittaker, R.J., Ladle, R.J., & Erhard, M. (2005). Reducing uncertainty in projections of extinction risk from climate change. *Global Ecology and Biogeography, 14*, 529–538.

Armstrong, R.L. (2010). The glaciers of the Hindu Kush–Himalayan region: A summary of the science regarding glacier melt/retreat in the Himalayan Hindu Kush Karakoram Pamir and Tien Shan mountain ranges. Retrieved from http://www.icimod.org/publications

Asahina, S. (1958). On a re-discovery of the larva of *Epiophlebia laidlawi* Tillyard from the Himalayas (Odonata, Anisozygoptera). *Tombo, 1*, 1–2.

Asahina, S. (1963). Description of the possible adult dragonfly of *Epiophlebia laidlawi* from the Himalayas. *Tombo, 6*, 18–20.

Bajracharya, S.R., Mool, P.K., & Shrestha, B.R. (2008). Global climate change and melting of Himalayan glaciers. In P.S. Ranade (Ed.) *Melting glaciers and rising sea levels: Impacts and implications* (pp. 28–46). India: Icfai University Press.

Bálint, M., Domisch, S., Engelhardt, C.H.M., Haase, P., Lehrian, S., Sauer, J., Theissinger, K., Pauls, S.U., & Nowak, C. (2011). Cryptic biodiversity loss linked to global climate change. *Nature Climate Change, 1*, 313–318.

Battisti, A., Stastny, M., Buffo, E., & Larsson, S. (2006). A rapid altitudinal range expansion in the pine processionary moth produced by the 2003 climatic anomaly. *Global Change Biology, 12*, 662–671.

Brockhaus, T., & Hartmann, A. (2009). New records of *Epiophlebia laidlawi* Tillyard in Bhutan, with notes on its biology, ecology, distribution, zoogeography and threat status (Anisozygoptera: Epiophlebiidae). *Odontologica, 38*, 203–215.

Burgmer, T., Hillebrand, H. & Pfenninger, M. (2007). Effects of climate-driven temperature change on the diversity of freshwater macroinvertebrates. *Oecologia, 151*, 93–103.

Corbet, P.S., Suhling, F., & Soendgerath, D. (2006). Voltinism of Odonata: A review. *International Journal of Odonatology, 9*, 1–44.

Cruz, R.V., Harasawa, H., Lal, M., Wu, S., Anokhin, Y., Punsalmaa, B., . . . Huu Ninh, N. (2007). Asia. In Parry, M.L., Canziani, O.F., Palutikof, J.P., van der Linden, P.J., & Hanson, C.E. (Eds.), *Climate change 2007: Impacts, adaptation and vulnerability*. *Contribution of working group II to the fourth assessment report of the Intergovernmental Panel on Climate Change* (pp. 469–506). Cambridge: Cambridge University Press.

De Block, M., McPeek, M.A., & Stoks, R. (2008). Life-history evolution when *Lestes* damselflies invaded vernal ponds. *Evolution, 62*, 485–493.

Domisch, S., Jähnig, S.C., & Haase, P. (2011). Climate-change winners and losers: Stream macroinvertebrates of a submontane region in Central Europe. *Freshwater Biology, 56*, 2009–2020.

Emori, S., Nosawa, T., Abe-ouchi, A., Numaguti, A., Kimoto, M., & Nakajima, T. (1999). Coupled ocean-atmosphere model experiments of future climate change with an explicit representation of sulfate aerosol scattering. *Journal of the Meteorological Society of Japan, 77*, 1299–1307.

Farnsworth, E.J., & Ogurcak, D.E. (2006). Biogeography and decline of rare plants in New England: Historical evidence and contemporary monitoring. *Ecological Applications, 16*, 1327–1337.

Fielding, A.H., & Bell, J.F. (1997). A review of methods for the assessment of prediction errors in conservation presence/absence models. *Environmental Conservation, 24*, 38–49.

Finch, J.M., Samways, M.J., Hill, T.R., Piper, S.E., & Taylor, S. (2006). Application of predictive distribution modelling to invertebrates: Odonata in South Africa. *Biodiversity and Conservation, 15*, 4239–4251.

Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C., & Weaver, A.J. (2000). The Canadian centre for climate modelling and analysis global coupled model and its climate. *Climate Dynamics, 16*, 451–467.

Gibson, L., McNeill, A., de Tores, P., Wayne, A., & Yates, C. (2010). Will future climate change threaten a range restricted endemic species, the quokka (*Setonix brachyurus*), in south west Australia? *Biological Conservation, 143*, 2453–2461.

Gordon, C., Cooper, C., Senior, C.A., Banks, H., Gregory, J.M., Johns, T.C., . . . Wood, R.A. (2000). The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics, 16*, 147–168.

Gordon, H.B., Rotstayn, L.D., McGregor, J.L., Dix, M.R., Kowalczyk, E.A., O'Farrell, S.P., . . . Elliott, T.I. (2002). The CSIRO Mk3 Climate System Model [Electronic publication]. Aspendale, CSIRO Atmospheric Research (CSIRO Atmospheric Research technical paper; no. 60), 130 pp.

Green, R. (1979). *Sampling design and statistical methods for environmental biologists*. New York: Wiley.

Guralnick, R. (2007). Differential effects of past climate warming on mountain and flatland species distributions: A multispecies North American mammal assessment. *Global Ecology and Biogeography, 16*, 14–23.

Hassall, C., & Thompson, D.J. (2008). The effects of environmental warming on Odonata: A review. *International Journal of Odonatology, 11*, 131–153.

Hassall, C., Thompson, D.J., & Harvey, I.F. (2010). The impact of climate-induced distributional changes on the validity of biological water quality metrics. *Environmental Monitoring and Assessment, 160*, 451–456.

Heino, J. (2002). Concordance of species richness patterns among multiple freshwater taxa: A regional perspective. *Biodiversity and Conservation, 11*, 137–147.

Heino, J., Virkkala, R., & Toivonen, H. (2009). Climate change and freshwater biodiversity: Detected patterns, future trends and adaptations in northern regions. *Biological Reviews, 84*, 39–54.

Hickling, R., Roy, D.B., Hill, J.K., Fox, R., & Thomas, C.D. (2006). The distributions of a wide range of taxonomic groups are expanding polewards. *Global Change Biology, 12*, 450–455.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., & Jarvis, A. (2005). Very high resolution interpolated climate surfaces for global land areas. *International Journal of Climatology, 25*, 1965–1978.

Hijmans, R.J., & Graham, C.H. (2006). The ability of climate envelope models to predict the effect of climate change on species distributions. *Global Change Biology, 12*, 2272–2281.

Hill, J.K., Thomas, C.D., Fox, R., Telfer, M.G., Willis, S.G., Asher, J., & Huntley, B. (2002). Responses of butterflies to twentieth century climate warming: Implications for future ranges. *Proceedings of the Royal Society of London Series B-Biological Sciences, 269*, 2163–2171.

Hof, C., Brandle, M., & Brandl, R. (2008). Latitudinal variation of diversity in European freshwater animals is not concordant across habitat types. *Global Ecology and Biogeography, 17*, 539–546.

Hosmer, D.W., & Lemeshow, S. (2000). *Applied logistic regression* (2nd ed.). New York: Wiley.

IPCC (Intergovernmental Panel on Climate Change) (2007). *Climate Change 2007: The physical science basis, contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, . . . H.L. Miller (Eds.). Cambridge, UK and New York, NY: Cambridge University Press.

IUCN (International Union for Conservation of Nature) (2010). Retrieved August 2, 2010, from http://www.iucnredlist.org/apps/redlist/search

Krishnaraj, R., & Pritchard, G. (1995). The influence of larval size, temperature, and components of the functional response to prey density on growth-rates of the dragonflies *Lestes disjunctus* and *Coenagrion resolutum* (Insecta, Odonata). *Canadian Journal of Zoology, 73*, 1672–1680.

Larrucea, E.S., & Brussard, P.F. (2008). Shift in location of pygmy rabbit (*Brachylagus idahoensis*) habitat in response to changing environments. *Journal of Arid Environments, 72*, 1636–1643.
Liu, X., & Chen, B. (2000). Climate warming in the Tibetan Plateau during recent decade. *International Journal of Climatology, 20*, 1729–1742.
Masters, Z., Petersen, I., Hildrew, A.G., & Ormerod, S.J. (2007). Insect dispersal does not limit the biological recovery of streams from acidification. *Aquatic Conservation: Marine and Freshwater Ecosystems, 17*, 375–383.
Mitra, T.R. (2002). Geographical distribution of Odonata (Insecta) of Eastern India. *Memoirs of the Zoological Survey of India, 19*, 1–208.
Moore, N.W. (compiler) (1997). *Dragonflies – status survey and conservation action plan. IUCN/SSC Odonata specialist group*. Gland, Switzerland and Cambridge, UK: IUCN.
Muhammed, A., Stewart, B.A., Shrestha, K.L., Ahmed, A.U., Chowdhury, A.M. (2004). *Water resources in South Asia: An assessment of climate change associated vulnerabilities and coping mechanisms*. Retrieved from http://www.apn-gcr.org
Nesemann, H., Shah, R.D.T., Shah, D.N., & Sharma, S. (2011). Morphological characters of *Epiophlebia laidlawi* Tillyard larvae, with notes on the habitat and distribution of the species in Nepal ('Anisozygoptera': Epiophlebiidae). *Odonatologica, 40*, 191–202.
Ni, J. (2000). A simulation of biomes on the Tibetan Plateau and their responses to global climate change. *Mountain Research and Development, 20*, 80–89.
Pandit, M.K. (2009). Other factors at work in the melting Himalaya: follow-up to Xu et al. *Conservation Biology, 23*, 1346–1347.
Parmesan, C. (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution, and Systematics, 37*, 637–669.
Parmesan, C. & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature, 421*, 37–42.
Pearson, R.G., & Dawson, T.P. (2003). Predicting the impacts of climate change on the distribution of species: Are bioclimate envelope models useful? *Global Ecology & Biogeography, 12*, 361–371.
Peterson, A.T., Soberon, J., & Sanchez-Cordero, V. (1999). Conservation of ecological niches in evolutionary time. *Science, 285*, 1265–1267.
Pickup, J., & Thompson, D.J. (1990). The effects of temperature and prey density on the developmental rates and growth of damselfly larvae (Odonata: Zygoptera). *Ecological Entomology, 15*, 187–200.
Pöyry, J., Luoto, M., Heikkinen, R.K., & Saarinen, K. (2008). Species traits are associated with the quality of bioclimatic models. *Global Ecology and Biogeography, 17*, 403–414.
R Development Core Team (2011). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. Retrieved from http://www.apn-gcr.org
Sauer, J., Domisch, S., Nowak, C., & Haase, P. (2011). Low mountain ranges: Summit traps for montane freshwater species under climate change. *Biodiversity and Conservation, 20*, 3133–3146.
Schmidt, E. (1985). Habitat inventorization, characterisation and bio indication by a Representative Spectrum of Odonata Species (RSO). *Odonatologica, 14*, 127–133.
Sharma, S., & Ofenböck, T. (1996). New discoveries of *Epiophlebia laidlawi* Tillyard, 1921 in the Nepal Himalaya (Odonata, Anisozygoptera: Epiophlebiidae). *Opuscula zoologica fluminensia, 150*, 1–11.
Shimura, S. (2005). *Dragonfly in the Kinki Region Zakki: Epiophlebia superstes*. Retrieved June 10, 2012, from http://tombon.com/ENGS002.htm
Shrestha, A.B., Wake, C.P., Mayewski, P.A., & Dibb, J.E. (1999). Maximum temperature trends in the Himalaya and its vicinity: An analysis based on temperature records from Nepal for the period 1971–94. *Journal of Climate, 12*, 2775–2786.
Song, M., Zhou, C., & Ouyang, H. (2004). Distributions of dominant tree species on the Tibetan Plateau under current and future climate scenarios. *Mountain Research and Development, 24*, 166–173.
Svihla, A. (1984). Notes on *Epiophlebia laidlawi* Tillyard. *Tombo, 27*, 26.
Sweeney, B.W., Jackson, J.K., Newbold, J.D., & Funk, D.H. (1992). Climate change and the life history and biogeography of univoltine aquatic insects in eastern Northern America. In P. Firth & S. Fisher (Eds.). *Global climate change and freshwater ecosystems* (pp. 143–176). New York: Springer-Verlag.
Tabaru, N. (1984). Larval development of *Epiophlebia superstes* in Kyushu. *Tombo, XXVII*, 1–4.
Tani, K., & Miyatake, Y. (1979). The discovery of *Epiophlebia laidlawi* Tillyard, 1921 in the Kathmandu valley, Nepal (Anisozygoptera: Epiophlebiidae). *Odontologica, 8*, 329–332.
Thuiller, W., Lafourcade, B., Engler, R. & Araújo, M.B. (2009). BIOMOD – a platform for ensemble forecasting of species distributions. *Ecography, 32*, 1–5.
Tillyard, R.J. (1921). On an Anisozygopterous larva from the Himalayas (Order Odonata). *Records of the Indian Museum, 22*, 93–109 + plate XIII.
Valtonen, P. (1986). On the Odonate fauna of a Finnish forest pond occasionally drying up. *Notulae Odonatologicae, 2*, 134–135.
Xu, J.C., Grumbine, R.E., Shrestha, A., Eriksson, M., Yang, X.F., Wang, Y., & Wilkes, A. (2009). The melting Himalayas: cascading effects of climate change on water, biodiversity, and livelihoods. *Conservation Biology, 23*, 520–530.
Yang, X.G., Zhang, T.J., Qin, D.H., Kang, S.C., & Qin, X.A. (2011). Characteristics and changes in air temperature and glacier's response on the north slope of Mt. Qomolangma (Mt. Everest). *Arctic Antarctic and Alpine Research, 43*, 147–160.

Yao, T., Pu, J., Lu, A., Wang, Y., & Yu, W. (2007). Recent glacial retreat and its impact on hydrological processes on the Tibetan Plateau China and surrounding regions. *Arctic Antarctic and Alpine Research, 39*, 642–650.

Zhang, X.S., Yang, D.A., Zhou, G.S., Liu, C.Y., & Zhang, J. (1996). Model expectation of impacts of global climate change on biomes of the Tibetan Plateau. In K. Omasa, K. Kai, H. Taoda, Z. Uchijima, & M. Yoshino (Eds.), *Climate Change and Plants in East Asia* (pp. 25–38 + xxv-xxxix) Tokyo: Springer-Verlag.